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Thermal Radiation Characteristics and
Thermophysical Properties of Lunar Material

Semi-Annual Technical Progress Report for 1972

Thermophysical Property Measurements on Lunar Fines from Apollos Missions

by

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Introduction

This report lists the published or to be published works performed on National Aeronautics and Space Administration contract no. NAS9-8098 from 1 January 1970 to 31 January 1971 and on Grant no. NGR 18-001-060 from 1 February 1971 to 1 September 1972. During this time period lunar samples from Apollos 11, 12, 14, 15 and 16 were received and studied.

This progress report reviews the thermophysical properties on lunar fines for a density of 1600 kg/m^3. There are a total of 26 publications which have resulted from our studies and a listing of the publication is attached.

Descriptions

General: lunar samples, thermophysical properties

Specific: spectral reflectance and emittance, thermal conductivity, density

List of publications National Aeronautics and Space Administration contract no. NAS9-8098 and grant NGR 18-001-060.

General papers

1. Birkebak, R.C., Cremers, C.J., and Dawson, J.P., "Thermal Radiation Properties and Thermal Conductivity of Lunar Materials," Science, vol. 167, no. 3918, Jan. 1970.

Thermal radiation papers

2. Birkebak, R.C., Cremers, C.J., and Dawson, J.P., Directional Spectral and Total Reflectance of Lunar Material," Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 1, vol. 3, pp. 1943-2000, Pergamon 1970.

3. Birkebak, R.C., Cremers, C.J., and Dawson, J.P., "Spectral Directional Reflectance of Lunar Fines as a Function of Bulk Density," Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta. Suppl. 2, vol. 3, MIT Press 1971.

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Thermal conductivity diffusivity papers

11. Cremers, C.J., Birkebak, R.C., and Dawson, J.P., "Thermal Conductivity of Fines from Apollo 11," Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta. Suppl. 1, vol. 3, Pergamon, pp. 2045-2050, 1970.

12. Cremers, C.J. and Birkebak, R.C., "Thermal Conductivity of Fines from Apollo 12," Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta. Suppl. 2, vol. 3, 1971, MIT Press.

13. Cremers, C.J., "Thermal Conductivity of Lunar Fines from Apollo 11," Proc. 5th Symposium on Thermophysical Properties, ASME, pp. 391-395, 1970.

14. Cremers, C.J., "Density, Pressure and Temperature Effects on Heat Transfer in Lunar Material," AIAA Journal, vol. 9, no. 11, pp. 2180-2183, 1971.

15. Cremers, C.J., "A Thermal Conductivity Cell for Small Powdered Samples," Rev. Sci. Inst., vol. 42, no. 11, 1971.

16. Cremers, C.J., "Low Temperature Lunar Thermophysical Properties," Proc. XIII International Refrigeration Conf. (in press).

17. Cremers, C.J., "Heat Transfer Parameters of the Lunar Surface Layer," Heat and Mass Transfer, vol. 7, Proc. IV All Union Heat and Mass Transfer Conference, Minsk, USSR (in Russian), pp. 584-596, 1972.

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19. Cremers, C.J., "Thermal Conductivity of Apollo 12 Fines at Intermediate Density, The Moon, vol. 4, pp. 88-93, 1972.

Lunar surface temperature calculations papers

20. Cremers, C.J., Birkebak, R.C., and White, J.E., "Lunar Surface Temperatures at Tranquillity Base," AIAA Journal, vol. 9, pp. 1899-1903, 1971.

21. Cremers, C.J., Birkebak, R.C., and White, J.E., "Lunar Surface Temperatures from Apollo 12," The Moon, vol. 3, pp. 346-351, 1971.

22. Cremers, C.J., Birkebak, R.C., and White, J.E., "Thermal Characteristics of the Lunar Surface Layer," Int. J. Heat and Mass Transfer, vol. 15, pp. 1045-1055, 1972.

Instrumentation and equipment papers

23. Birkebak, R.C., Cremers, C.J., and Lyons, W.E., "Vacuum Handling System for Powdered Samples," Rev. of Sci. Inst., vol. 42, pp. 1715-1717, Nov. 1971.

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26. Birkebak, R.C. and Watkins, J., "A General Method for Determining the Thermophysical Properties of Insulting Materials Using an Extension of the Line Heat Source Technique," XI International Conference on Thermal Conductivity, p. 41-42, Sept. 1971.

Spectral Directional Reflectance and Emittance of Lunar Fines:

The smooth curves for our data which are shown in the following figures are a fit through data points taken at 0.02 μm interval to 1.0 μm, 0.05 μm interval to 2.2 μm, and 0.25 μm interval to 14.5 μm.

The spectral directional reflectance curves for fines from Apollo Missions 11, 12, 14, 15 and 16 are shown in Fig. 1. The results are for a bulk density of approximately 1600 kg/m^3 for each sample and for an angle of illumination of approximately 10°. It is difficult sometimes to identify absorption bands in the fines data. However, the pyroxene band near 1.0 μm is apparent in Apollo 12, 14 and 15 samples but undetectable by us in the Apollo 11 and 16 samples. The results of Adams and Jones [1], and Conel and Nash [2] show a single very shallow absorption band centered at 0.95 μm for the Apollo 11 sample. Other investigators [3], however, did not find any band features in this region of the spectrum.

Both the results of Birkebak and Dawson [4] and Adams and McCord [5] show an absorption band for the Apollo 14 sample centered at 0.93 μm and this band is due to pyroxene [5]. Also a band is clearly evident at 1.8 μm.

The variation in reflectance from one Apollo sample to another is associated with its chemical composition and glass content [1,2,5,6,7,8]. As the lunar fines become 'lighter in color', an increase in reflectance, we find fewer opaq ue materials in the fines. Adams and McCord [5]

have discussed the lighter appearances of Apollo 14 fines and relates it to the fines having lower overall iron and titanium content. The presence or absence of the absorption bands are a function of the dark glass content and the crystal/glass ratio. The disappearance of the pyroxene band near 1 μm may be caused also instead by extensive impact melting and shock aleration of the soil [7]. Material taken from the core tube samples or trench below 70 mm or so from the surface has a higher reflectance than the surface fines. The darkening of the surface material takes place due to meteorite impact-induced vitrification and by regional contamination by iron and titanium rich mare material.

The average composition of the Apollo 11, 12, 14, 15 and 16 fines are given in table1[9,10]. B. Glass [11] has reported that glass particles in the fines with low TiO_2 and FeO content (< 1%) and high Al_2O_3 (approx. 33%) are colorless: as the TiO_2 and FeO content increase approximately 3% and 20%, respectively and with a decrease in Al_2O_3 from 33% to 10%, the color of the glass changes from transparent pale green to yellow-green to yellow-brown to red and dark opaque red-brown.

The crystal to glass ratio is also an indication of the maturity [5] of the material, Apollo 11 fines were approximately 50% glass, Apollo 12, 20% glass and Apollo 14, 40 to 75% glass [5].

Our Apollo 11, 12 and 15 samples can be classified as mare material and Apollo 14 and 16 as lunar highlands material.

The spectral reflectances reported by other investigators show similar trends as ours. It is difficult to compare the results since

they refer their reflectances to MgO samples and do not give the bulk density of their material.

The solar reflectance were calculated from the spectral directional reflectance, spectral emittance results to be discussed in the next section and the spectral solar distribution. The solar reflectance (albedo) is defined as

$$\rho_s(\theta) = \frac{\int_{\lambda=0.3}^{\lambda=6.0} \rho(\lambda, \theta)\, S_\lambda\, d\lambda}{\int_{\lambda=0.3}^{\lambda=6.0} S_\lambda\, d\lambda} \tag{1}$$

where $\rho(\lambda, \theta)$ is the spectral directional reflectance, θ is the angle of illumination, λ is the wavelength, and S_λ the spectral value of the incident solar energy.

The solar reflectance for the Apollo 11, 12, 14 and 15 samples are presented in Table 2 [4, 12, 13]. Clearly evident is both a bulk density and angle of illumination effect. The change in solar reflectance with angle of illumination is characteristic of dielectric materials.

The emittance results from Apollo 12, 14 and 15 are compared in Fig. 2 for a density of 1600 kg/m^3. All results have maximum emittance between 8 μm to 9 μm. The maximum emittance occurs at the so-called Christiansen frequency where the index of refraction of the surrounding medium and fines are equal and where internal scattering is a minimum. The Apollo 12 sample has a maximum emittance of 0.995 at approximately

8.5 μm. The Apollo 14 maximum emittance is at approximately 8.25 μm and Apollo 15 at approximately 8.4 μm. Logan et al. [14] have also measured the emittance for Apollo 14 sample 14259 over a smaller wavelength range than ours. They do not specify a bulk density for their measurement. They report a maximum emittance at 8.24 μm. Agreement of their results with ours is excellent. All samples have minimums at approximately 3.5 to 3.6 μm. Minimum value for Apollo 14, the lowest for all samples tested is 0.60, for Apollo 12 the minimum is 0.73.

Thermal Conductivity of Lunar Fines

The measured thermal conductivity data for the Apollo 14 sample at densities of 1100 and 1300 kg/m^3 respectively are given in Tables 3 and 4. Elementary theory predicts a cubic dependence of the thermal conductivity on temperatures. This was found to be a fair representation in the present case as it was in the previous investigations of the Apollo 11 and 12 samples. Consequently, the numerical data are conveniently represented by $k = A + BT^3$ for which the constants were obtained by a least-squares analysis. This equation is also plotted in Figures 3 and 4 and the coefficients are given in Table 5. Consideration of the accuracy of representation of the data by such an equation suggests that a cubic dependence on temperature is probably the case. However, because of data scatter and present lack of data at lower temperatures, the evidence is far from conclusive.

The data given for the Apollo 11, 12, and 14 samples are not yet sufficiently complete for a critical analysis of the temperature dependence

of the thermal conductivity. On the other hand, the Fountain and West data for terrestrial basalt, [15], taken at a number of densities ranging from 790 to 1500 kg/m^3 are extensive. These were much larger samples and so the errors should be expected to be less significant. Analysis of these data shows that a cubic least-squares fit works well in some cases (one such case is the density of 1300 kg/m^3) but not so well for other densities. For the Apollo 12 and 14 samples the agreement is best at higher temperatures but in general is good. This suggests that the elementary theory is close to correct but that perhaps some vital elements are still missing.

A curve of the form $k = AT^{-1} + BT^3$ (suggested in a review by Kanamori of a previous paper by C. J. Cremers) reflecting an inverse temperature dependence for the lattice component of the conductivity was also tried for the Apollo 11 and 12 fines. The fit was acceptable at high temperatures but not at the low end of the range. This lack of success is probably due to the somewhat amorphous nature of the finely divided lunar samples. No attempt was made to fit this curve to the present data.

It is of interest to compare the thermal conductivity of the Apollo 14 fines with that of other samples. However, in the present case, this is possible only with the higher of the two densities used as it was not possible to achieve such a comparably low density with the Apollo 11 and 12 fines. In both cases it was not possible to prepare a sample with a density less than about 1300 kg/m^3. As a consequence it is

possible to compare the 1100 kg/m^3 sample of Apollo 14 fines with only terrestrial basalt at a density of 1130 kg/m^3. These data are presented by Fountain and West [15]. They fitted a cubic curve to their data and the results are shown in Fig. 3. The coefficients of the cubic equation are given in Table 5. The agreement between the basalt and Apollo 14 fines is outstanding in this case although there is no particular reason why it should be so. Figure 4 includes curves for the basalt as well as for the Apollo 11 and 12 data, all at the density of 1300 kg/m^3. The basalt data, again from Fountain and West [15] are represented by cubic least-squares curves as are the Apollo 11 data of Cremers _et al._ [17] and the Apollo 12 data of Cremers and Birkebak [18]. Because of its similarity in chemical composition to the lunar fines, basalt is probably the best terrestrial material for comparison. Agreement between the data for the several samples is not so good in this case. However, note that for the Apollo 14 sample, the conductivities at the two densities are nearly the same.

It is of interest to note that the magnitudes of all the conductivities shown in Fig. 4 are roughly the same. What is of perhaps more importance, however, is the apparent difference in temperature dependence between the different sets of data shown. The slope of each curve, at a given value of the temperature is an indication of the magnitude of the radiative component which is expressed through the coefficient B. It appears that the radiative effects in the terrestrial basalt are slightly less important than in the Apollo 12 and 14 samples but of slightly

greater magnitude than in the Apollo 11 sample. Most probably, the causes of these deviations are differences in particle size distribution and possibly shape as well as variations in the amounts of glassy material present in each of the lunar samples.

The data of Fountain and West [15] are for particulate basalt 37 – 62 μm in diameter. That is a much narrower size range than was found the Apollo lunar fines, e.g. Gold et al. [3, 16, 19]. The abundance of micron sized and smaller particles in the latter samples would tend to suppress the radiative transfer mode as the powder would more closely resemble a solid. The study of Watson [20] indicated that the radiative component in powdered media depends strongly on particle size, being much more important for larger particles on the order of 100 μm diameter than for particles on the order of 10 μm diameter. The Apollo 12 data indicate that there is perhaps a greater abundance of larger particles present resulting in stronger radiative effects. That this is so is evidenced by the comparison of particle sizes from the fines samples of all three Apollo missions as presented by Gold et al. [19].

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Table 1
Average composition of Lunar fines

Compound	10084[a]	12070[a]	14163[a]	15021[a]	68841[b]
			Lunar Sample No. abundance, percent		
SiO_2	41.86	45.91	47.17	46.56	45.08
TiO_2	7.56	2.81	1.79	1.75	0.59
Al_2O_3	13.55	12.50	17.22	13.73	26.49
FeO	15.94	16.40	10.35	15.21	5.65
Mn O	.21	.22	.14	.20	0.07
MgO	7.82	10.00	9.37	10.37	6.27
CaO	12.08	10.43	10.95	10.54	15.30
Mg_2O	.40	.41	.66	.41	0.41
K_2O	.13	.25	.58	.20	0.11
P_2O_5	.11	.27	.46	.18	0.12
S	.15	.08	.08	.06	0.08
Cr_2O_3	.32	.43	.22		
Total	100.13	99.71	98.99	99.21	100.16

[a] Apollo 15 Preliminary Science Report NASA-SP289, 1972

[b] Apollo 16 Lunar Sample Information Catalog, LRL, NASA-MSC 03210, July 1972.

Table 2 [13]
Solar Albedo for Lunar Fines

Angle of illumination (degrees)	Apollo 11 10084 Density (kg/m^3)				Apollo 12 12070 Density (kg/m^3)		
	1300	1400	1600	1800	1300	1600	1800
10	0.076	0.087	.099	.101	.101	.119	.120
20	0.082	.095	.	.102	.106	.114	.126
30	0.084	.102	.107	.108	.109	.115	.131
45	0.095	.113	.113	.116	.122	.136	.138
60	0.108	.132	.133	.132			

Table 2 [cont.]

	Apollo 14 [4] 14163 Density (kg/m^3)			Apollo 15 15041 Density (kg/m^3)
	1095	1300	1590	1615
15	0.18	0.212	0.213	0.137
30	0.194	0.222	0.221	0.146
45	0.216	0.241	0.262	0.162
60	0.250	0.281	0.297	0.193

Table 3. Apollo 14 Thermal Conductivity Data - 1100 kg/m^3

Temperature (K)	Thermal Conductivity (W/m - K)
353	1.64×10^{-3}
352	1.67
351	1.75
350	1.69
344	1.63
337	1.70
329	1.60
328	1.60
314	1.72
313	1.64
387	1.31
285	1.36
284	1.33
283	1.36
274	1.27
271	1.23
260	1.12
256	1.09
252	1.02
245	1.16
219	0.98
210	0.94
185	1.13
181	1.02
179	0.99
178	0.75
156	0.73
142	1.04
139	0.79
126	0.89
126	1.09
122	0.90

Table 4. Apollo 14 Thermal Conductivity Data - 1300 kg/m^3

Temperature (K)	Thermal Conductivity (W/m - K)
404	2.16×10^{-3}
404	2.23
390	2.27
389	2.36
389	2.41
367	1.68
367	1.74
367	1.97
367	1.77
359	1.98
343	1.73
340	1.75
326	1.61
321	1.62
321	1.54
320	1.59
319	1.56
296	1.40
295	1.24
295	1.35
292	0.98
277	0.95
240	0.90
231	1.07
221	1.04
214	0.97
208	0.95
201	0.95
109	0.78
109	0.68

Table 5. Coefficients of $k = A + BT^3$

Sample	Density (kg/m^3)	$A \times 10^3$ (W/m - K)	$B \times 10^{11}$ ($W/m - K^4$)
Apollo 14	1100	0.836	2.09
Apollo 14	1300	0.619	2.49
Apollo 12	1300	0.922	3.19
Apollo 11	1300	1.42	1.73
Basalt[a]	1130	0.887	1.90
Basalt[a]	1300	1.24	2.43

[a] Basalt values are from Fountain and West [15].

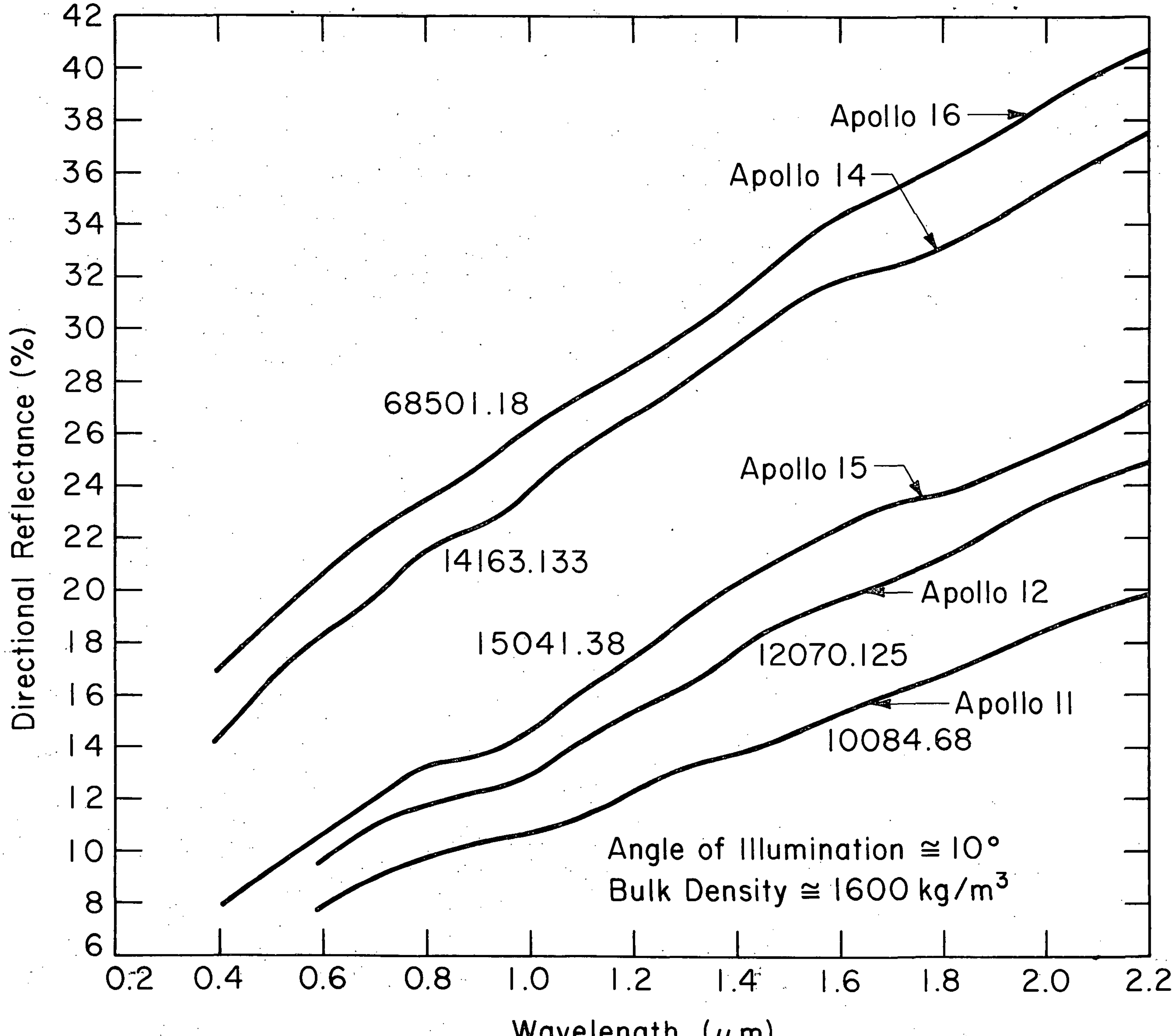

Figure 1. Spectral Directional Reflectance of Lunar Fines

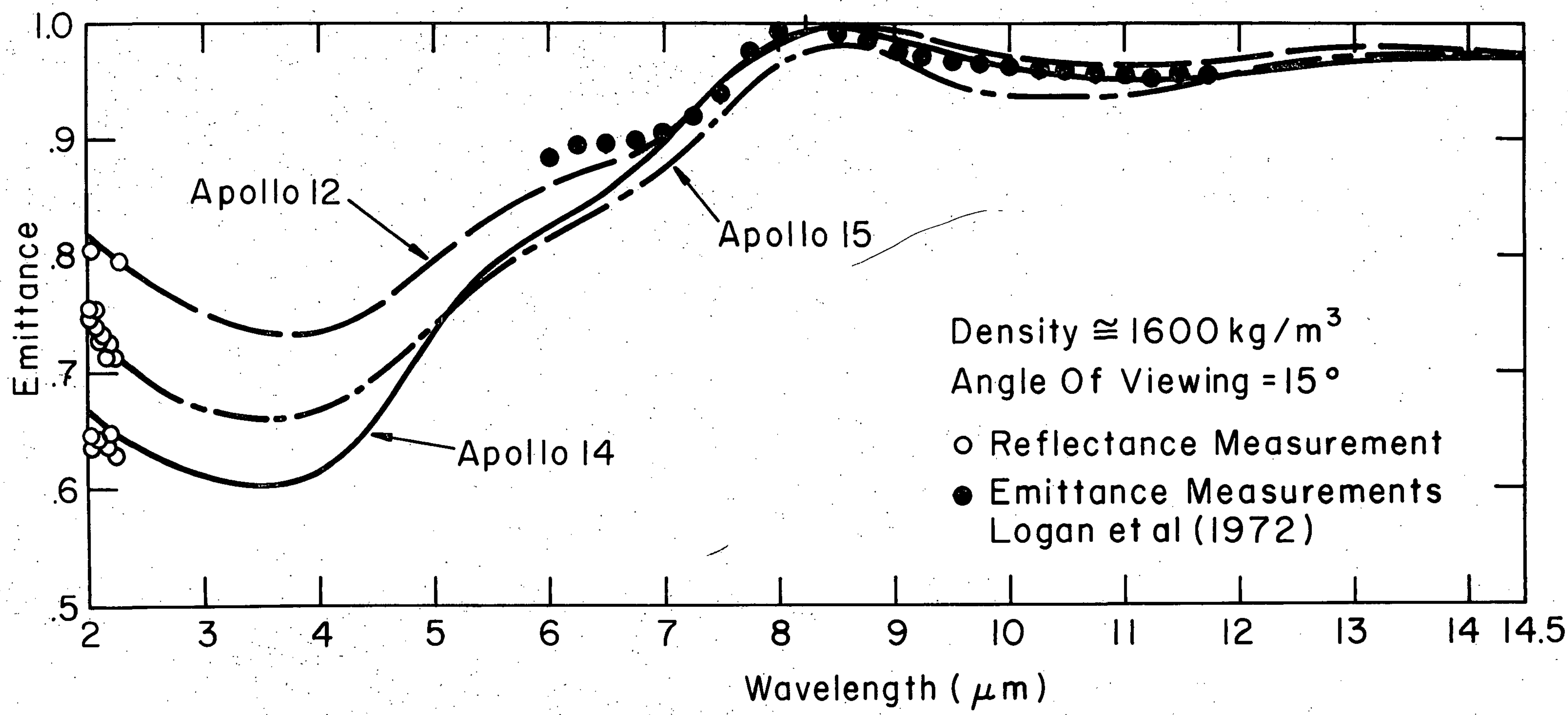

Figure 2. Spectral Emittance of Lunar Fines

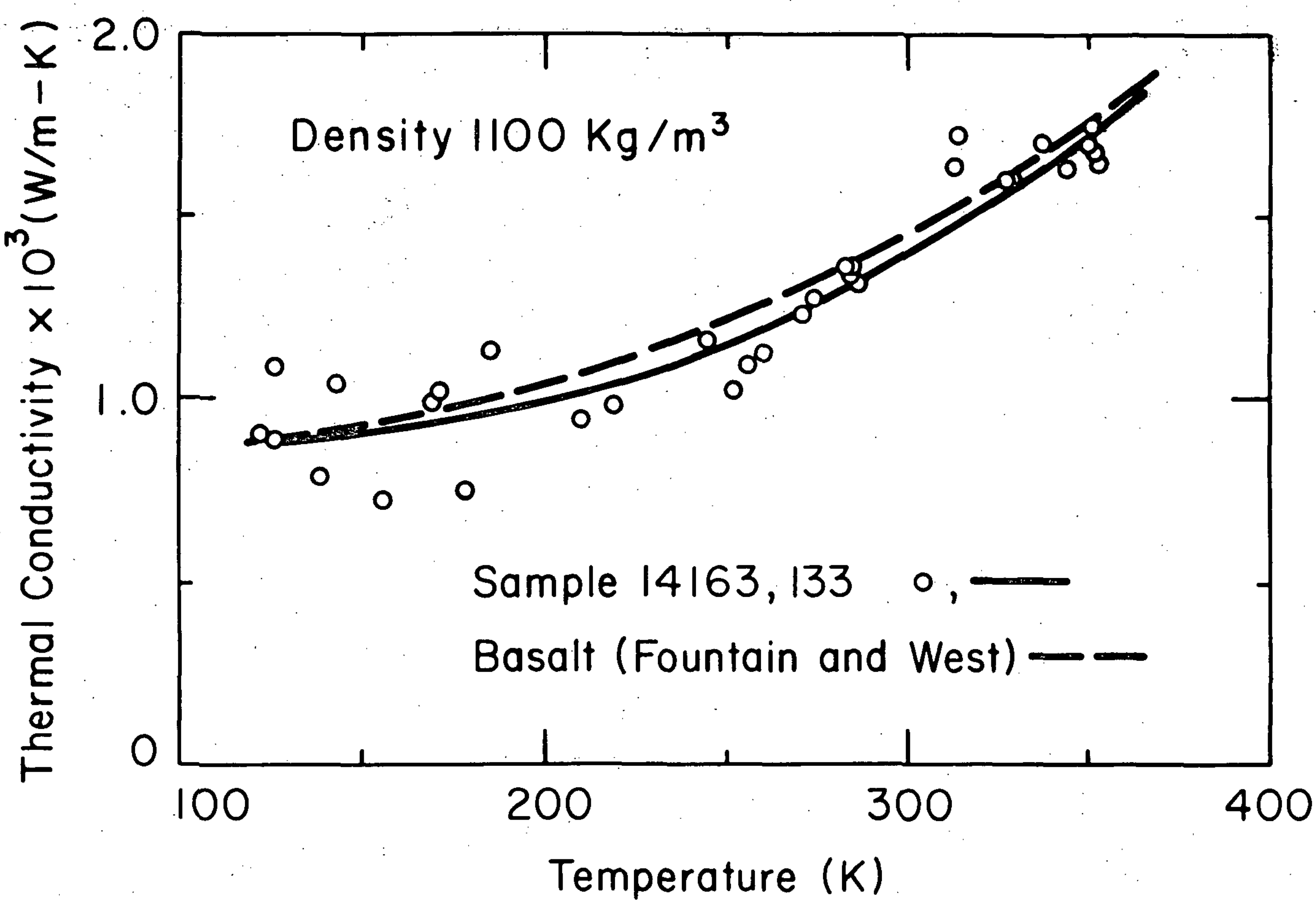

Figure 3. Thermal conductivity of fines at a density of 1100 kg/m^3.

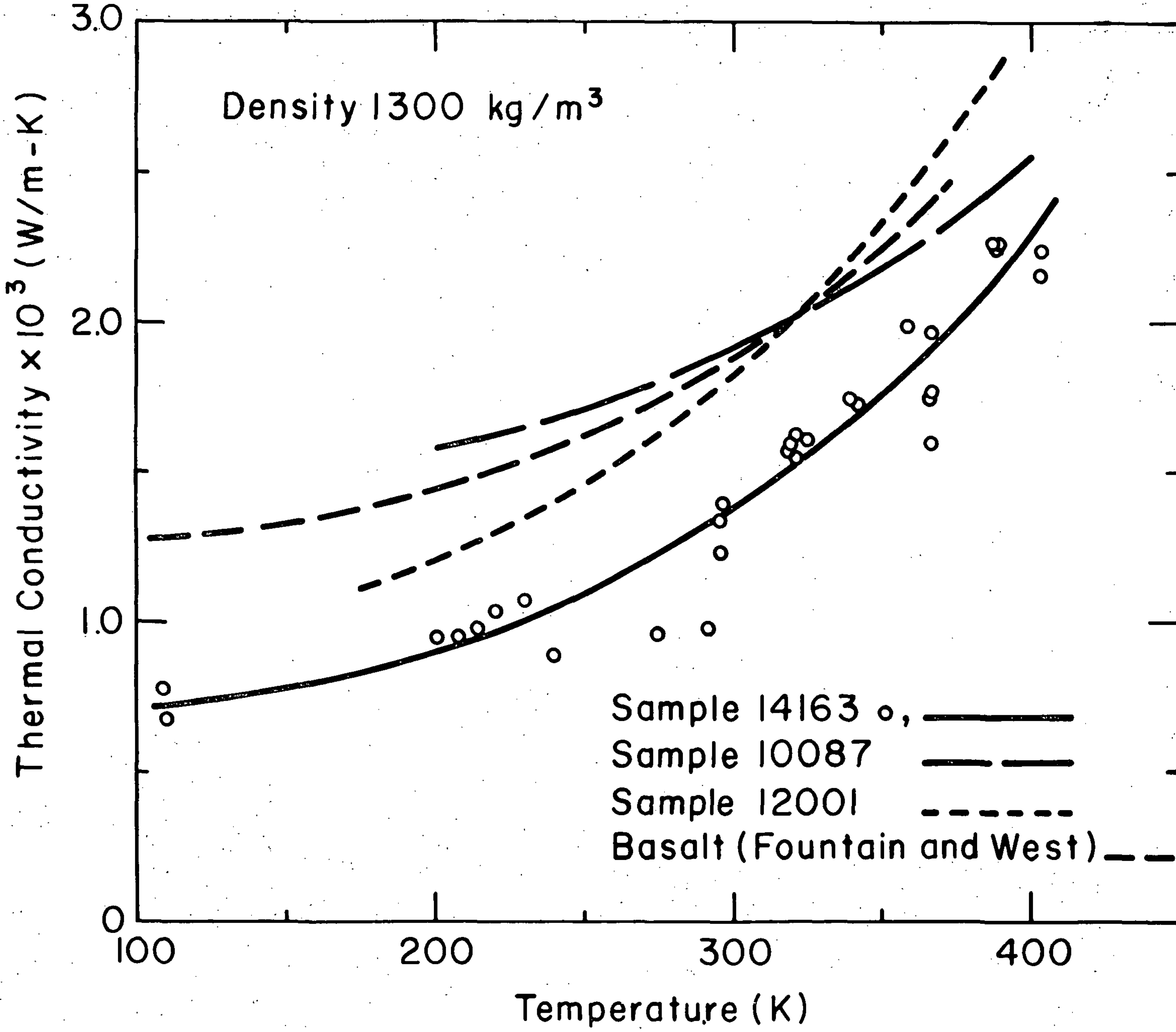

Figure 4. Thermal conductivity of fines at a density of 1300 kg/m^3.